

THE NORTH AMERICAN BLIZZARD OF 2009: A SYNOPTIC REVIEW

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ABSTRACT

A powerful winter storm crippled much of the eastern United States and Canada during mid-December 2009. What would later become known as the North American Blizzard of 2009, this storm produced record snowfall amounts for the month at numerous locations across the Mid Atlantic and New England regions and resulted in seven fatalities.

This paper will examine the synoptic and mesoscale conditions present as the event unfolded from 0000 UTC 17 Dec to 0000 UTC 21 Dec 2009. The event can be categorized as a Miller A type storm which developed in the Gulf of Mexico on 16 Dec and produced copious amounts of snowfall from North Carolina to Nova Scotia between 18-20 Dec 2009. A review of the North Atlantic Oscillation (NAO) pattern indicates a strong negative pattern during the month which is more favorable for the development of strong wintertime storms. A synoptic review is the first step in understanding why this event occurred so early in the winter season and may shed light on new avenues of research relating NAO and severe winter weather.

1. INTRODUCTION

One of the worst snow storms in decades to affect eastern North America occurred on 16 Dec to 20 Dec 2009. It brought heavy rain to the southern United States as well as record December snowfall amounts and blizzard warnings to the Mid-Atlantic and New England areas. The Canadian Atlantic maritime provinces of Nova Scotia and New Brunswick also saw heavy snow. Seven fatalities were reported due to the event and heavy snow crippled ground and air travel for several days.

Development began over the northwestern Gulf of Mexico on 16 Dec 2009 with a stationary front stretching from Mexico across the Gulf to

southern Florida. A dome of high pressure, with cold continental polar air, was firmly entrenched across the eastern United States. A 1015 hectopascal (hPa) low pressure system developed on 17 Dec 2009 just off the coast of Texas and then began a trek east-northeastward. By Saturday 19 Dec 2009 the low pressure had deepened to 996 hPa and was located near Savannah, Georgia. Snowfall was already occurring by this time across the southern Appalachians as both Gulf and Atlantic moisture converged and clashed with cold air over the area. By 1200 UTC 19 Dec 2009 the system had moved to the Outer Banks region of North Carolina and continued to show signs of strengthening with a core pressure drop to 986 hPa. Heavy snow was falling over northern Virginia, Washington D.C., and Maryland. New England started seeing accumulations the afternoon of the nineteenth as the low made its way off the coast of New Jersey. The system began to exit the region by 0000 UTC on 21 Dec 2009 leaving in its wake heavy snowfall, strong winds, and reduced visibilities.

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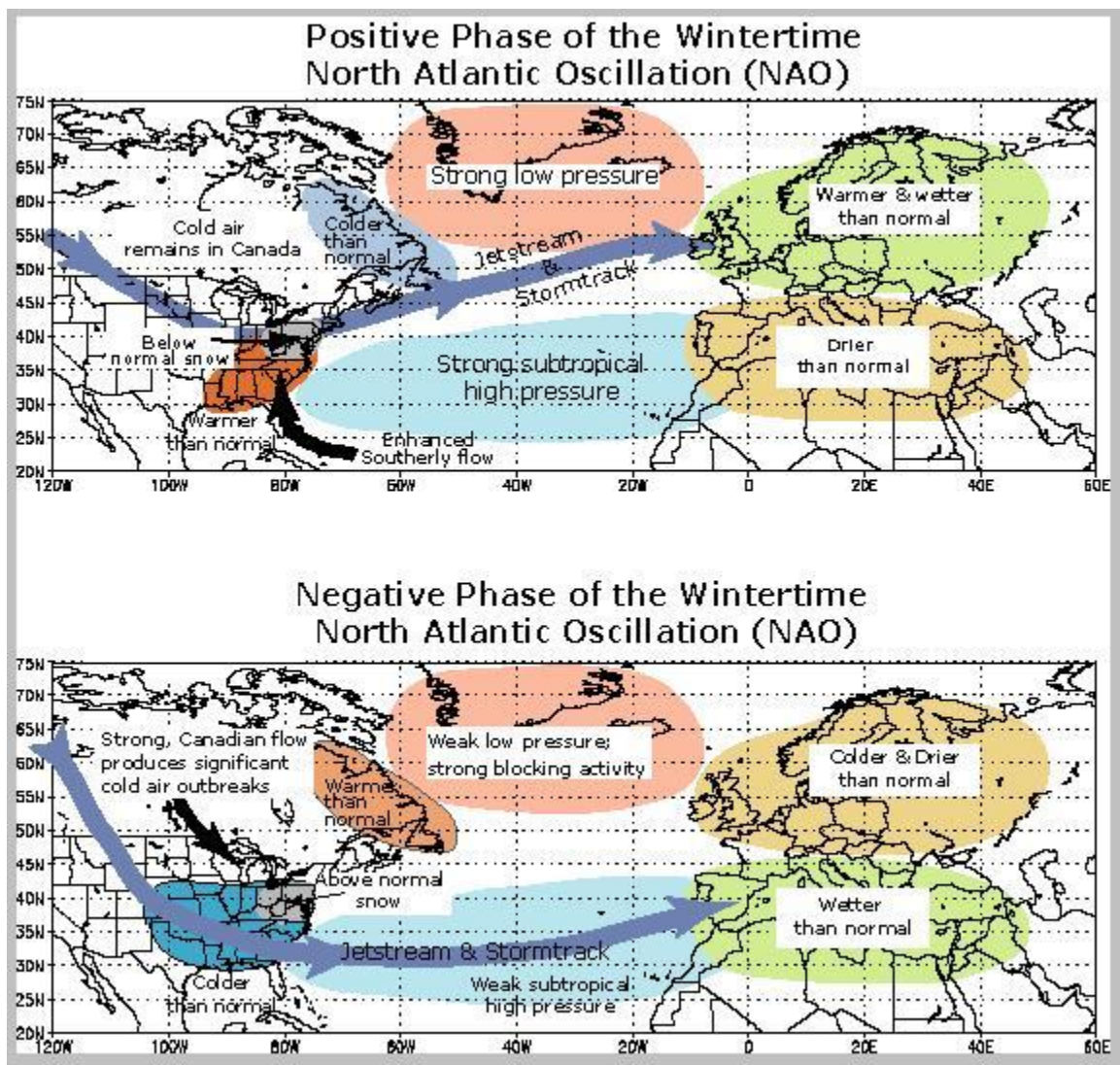


Figure 1. The wintertime North Atlantic Oscillation (courtesy of NCDC). **A) Top:** Positive phase (+NAO) where a strong Azores high and Icelandic low result in zonal flow with reduced snowfall over the eastern United States. **B) Bottom:** Negative phase (-NAO) results in meridional flow and a southern track to the jet stream, bringing cold Canadian air and above normal snow to the northeastern U.S.

The North American Blizzard of 2009 was an early season snow storm that caught many residents along the East Coast off guard. The event can possibly be attributed to a strong negative North Atlantic Oscillation (NAO) which was in place for much of the winter of 2009/10. A synoptic review is the first step in understanding why this event occurred so early in the season and may shed light on new avenues of research relating NAO and severe winter weather.

2. CLIMATOLOGY

2.1 North Atlantic Oscillation

The North Atlantic Oscillation (NAO) describes the differences in location and atmospheric pressure between low and high pressure systems over the North Atlantic. It is one of three empirically derived numbers that represent the location of temperature and pressure over large ocean areas (Glickman et

al. 2000). In a +NAO setup during the wintertime, a strong high pressure system over the Azores in combination with an Icelandic low forces the jet stream north into a more zonal pattern (Fig. 1a). This configuration leads to warmer than normal conditions in the eastern United States, thus reducing overall snowfall amounts. Northern Europe typically sees warmer conditions with above average precipitation during a +NAO phase, while northern Africa and the Greek Isles have less precipitation than average. The jet stream becomes more meridional in a -NAO phase as both the Azores high and Icelandic low pressure systems weaken. This results in storms taking a more southerly track as an enhanced trough sets up across the eastern United States which brings cold, snowy conditions the Mid-Atlantic and one cannot associate a particular storm event with positive

or negative NAO values; however, it can theorized that the strongly negative NAO during D-J-F 2009/2010 may correlate with the record amounts of snowfall observed over eastern North America for that time period.

2.2 Synoptic Setup of Heavy Snow Events over eastern North America

Major snowstorms in eastern North America can be grouped into several distinct categories of cyclogenesis. These are based on synoptic scale arrangements of low and high pressure systems, storm track, and the lifting mechanisms observed (Miller 1946). They include: Miller A cyclogenesis, Miller B cyclogenesis, closed upper level low, northwest upslope flow, overrunning, and the Alberta Clipper system. Each form is diagrammed in Figure 3.

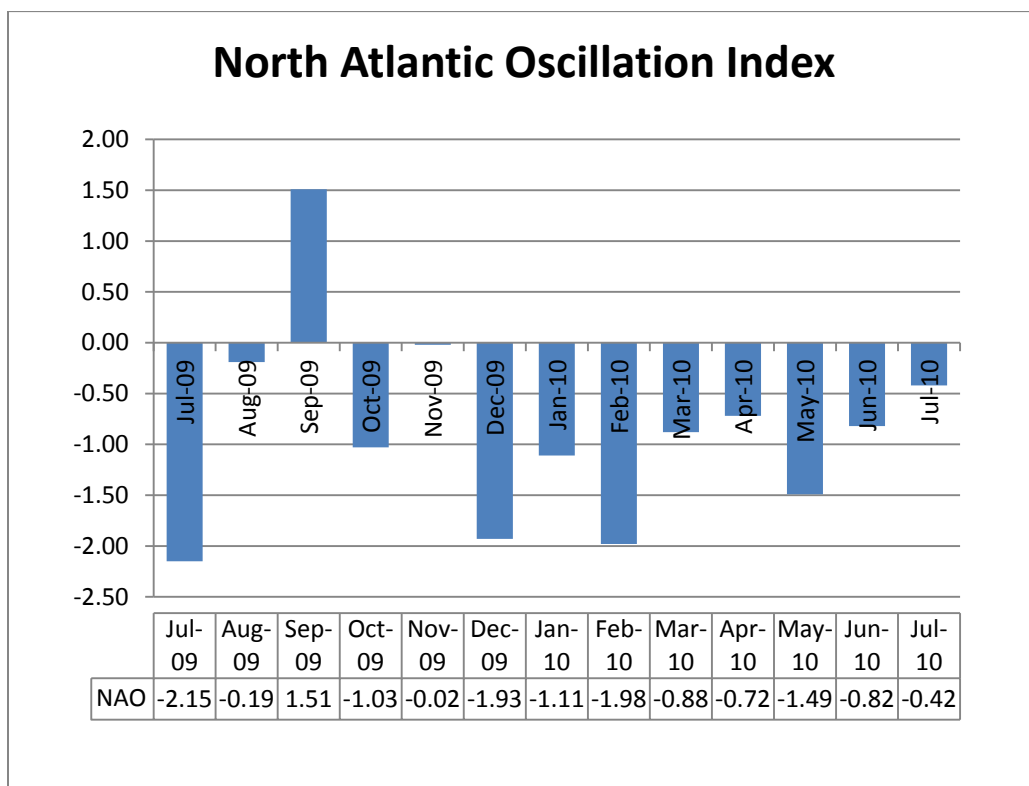


Figure 2. North Atlantic Oscillation (NAO) teleconnection indices from July 2009 to July 2010. Data obtained from NOAA's Climate Prediction Center.

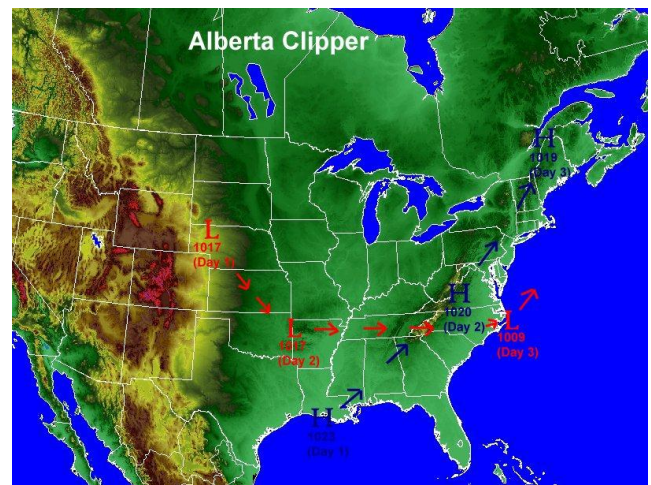
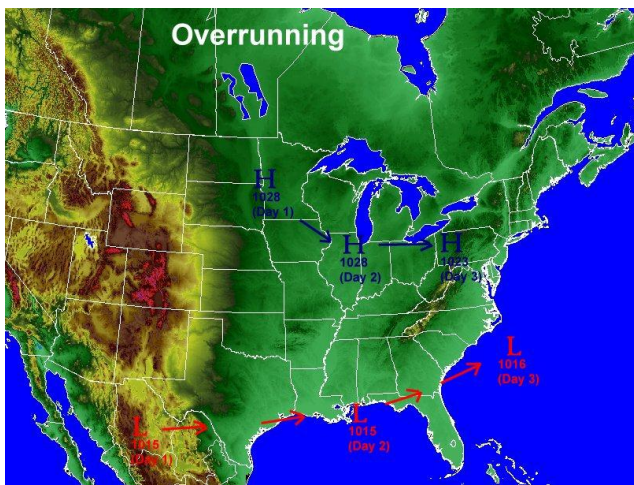
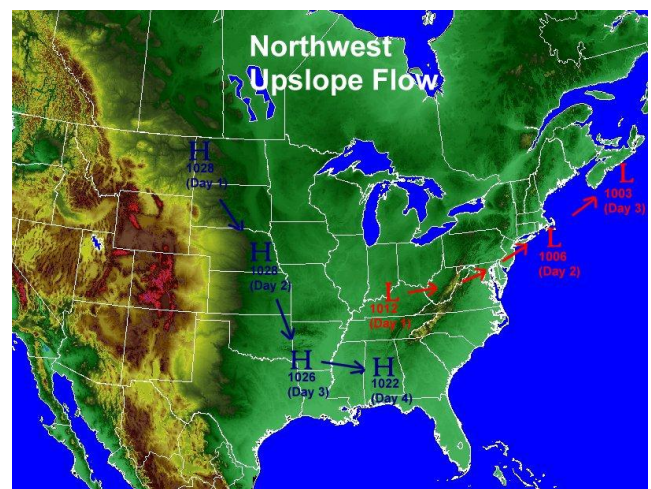
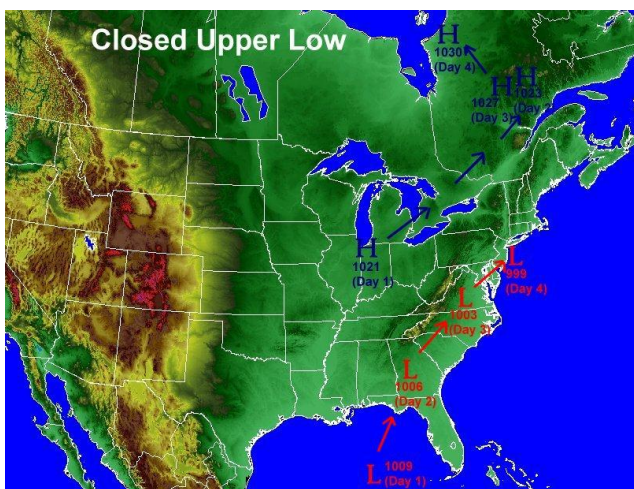
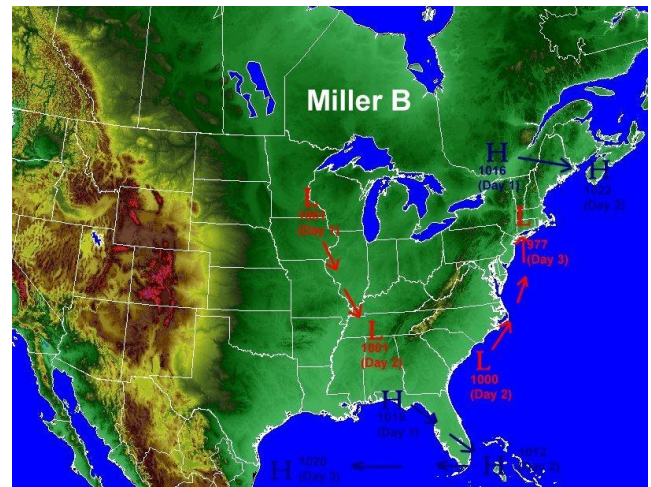
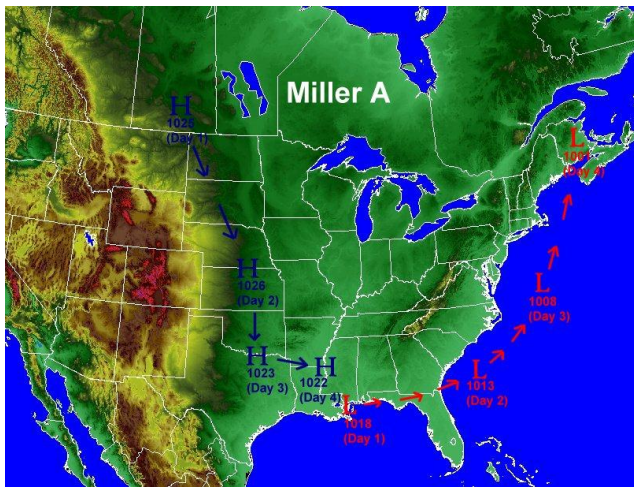


Figure 3. Synoptic setup of heavy snow events. **A) Top left:** Miller A cyclone; **B) Top right:** Miller B cyclone; **C) Middle left:** Closed upper level low; **D) Middle right:** Northwest upslope flow; **E) Lower left:** Overrunning; **F) Lower right:** Alberta Clipper system. Images courtesy NWS, RNK.

Cyclogenesis in the form of a Miller A storm system includes the development of a low pressure system over the Gulf of Mexico with strong high pressure over the north-central United States. With the progression of time, the developing low will track off to the northeast, gaining strength and finally moving up the seaboard of the East Coast toward the Canadian Maritime provinces. High pressure will slowly move southward, reinforcing cold air advection into eastern North America. This is the favored setup for development of major east coast snowstorms that produce snow totals measured in feet rather than in inches, including the North American blizzard of 1996 which dumped over 3 feet of snow across the Mid-Atlantic region.

Figure 3a provides an overview of the development and track of a Miller A cyclone. Miller B low pressure systems (Fig. 3b) originate over the Midwest United States and slowly make their way southward toward the Gulf of Mexico. High pressure dominates the northeast U.S. as well as along the Gulf Coast states. This arrangement of the two high pressure systems forces the Midwest low to stall over the south while a secondary low pressure system develops off the southeast coast. This is followed by weakening of the high pressure system over New England and the Miller B storm is carried northeast with the jet stream (Gurka et al. 1995). Miller B cyclones can produce heavy snowfall, such as during late December 1997 when the central Appalachians received over a foot; however, the bulk of precipitation usually begins as snow and quickly transitions to sleet or freezing rain as cold air damming along the Appalachians erodes.

Closed, upper level low pressure systems (Fig 3c) develop over the Gulf of Mexico and move extremely slowly off to the north and east. Precipitation over eastern North America can last for several days with the heaviest amounts occurring with strong dynamics northwest of the low pressure system and storm track. Depending on the overall setup, mountainous

areas in the central and southern Appalachians tend to see the highest snowfall amounts with closed low systems (Jackson 2010).

One of the most localized heavy snow events is categorized by northwest upslope flow (Fig. 3d). With this type of event there is strong low level flow of cold air across the Great Lakes, usually occurring with the passage of a strong low pressure system to the south. Moisture is transported southeastward which interacts with the central and southern Appalachians, is lifted and produces heavy, localized snowfall (Keighton et al. 2009).

Overrunning (Fig 3e) occurs with the passage of a weak low pressure system to the south of a strong dome of high pressure. Precipitation occurs as moist air overrides the cold air in place over the northeast U.S. Heavy snow can occur in bands associated with a warm front that tries to develop aloft. Just as with northwest upslope flow, heavy snowfall is localized (Jackson 2010).

Finally, Alberta Clipper systems develop over Alberta, Canada along the lee-side of the Canadian Rockies. They track to the southeast over the High Plains and then move off to the east toward the Atlantic Ocean (Fig. 3f). If a clipper system moves well enough to the south, the central and southern Appalachians can see moderate snowfall accumulations north of the low pressure track. Locations to the south of the clipper usually see light rain or snow (Jackson 2010).

The December 16-19, 2009 event can clearly be categorized as a Miller A cyclone due to the development of the low pressure system over the Gulf of Mexico which moved northeast along the East Coast in the presence of high pressure over the Great Plains. The evolution of the cyclone from its formation in the Gulf to eventual death and occlusion in the North Atlantic will be the main focus of the following sections.

3. SYNOPTIC OVERVIEW

3.1 0000 UTC – 17 Dec 2009 to 0000 UTC – 18 Dec 2009

A rather zonal flow at 500 hPa existed over the majority of the United States at 0000 UTC 17 Dec 2009. A weak trough was beginning to exit the northeast U.S. with an associated 100 knot jet max at 500 hPa over northern Virginia. The western two thirds of the country was dominated by tranquil weather; however, an upper-level disturbance was bringing moisture onshore along the southern Texas coast. This disturbance had remained cut-off from the northern polar jet since earlier that week and was bringing upper-level divergence to the western Gulf of Mexico (Fig. 4). This upper-level divergence, coupled with potential vorticity advection off of the Eastern Sierra

Madre's (and a deepening trough) later help in the formation of a surface low pressure over this exact area. Water vapor imagery from 0000 UTC 19 Dec show plenty of moisture present over the entire southern U.S. with a strong dryline located over central Texas associated with the closed upper-level system. Surface observations supported this with dew point temperatures in the negative single digits (°C) in western Texas while east of the dryline dew points ranged from the mid-single digits to the teens. Surface analysis indicated a stationary front existed just off the coast from Brownsville, TX and stretched eastward to southern Florida. High pressure dominated the eastern U.S. from the Great Lakes to Kentucky with the highest pressure recorded at 1034 hPa over southern Indiana.

By 1200 UTC on 17 Dec, a trough began to

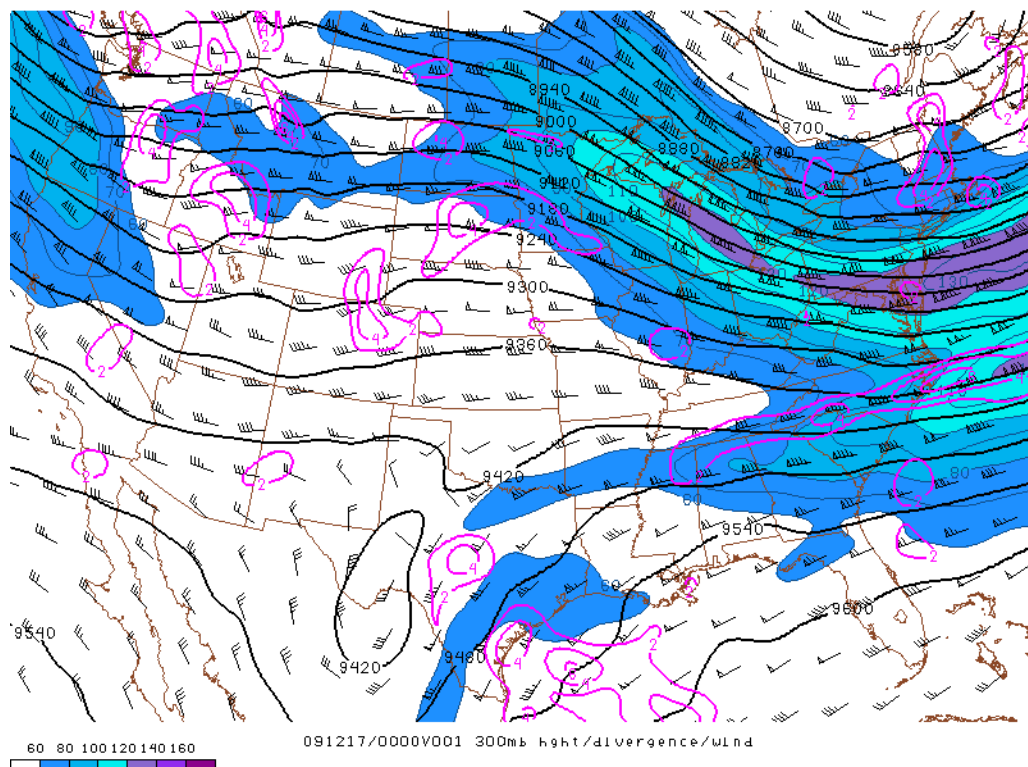


Figure 4. 300 hPa analysis chart with height (solid black lines), divergence (magenta lines), and wind (color fill and vectors) plotted, valid 0000 UTC 17 Dec 2009. Note the weak closed system over northern Mexico bringing upper-level divergence to the western Gulf of Mexico.

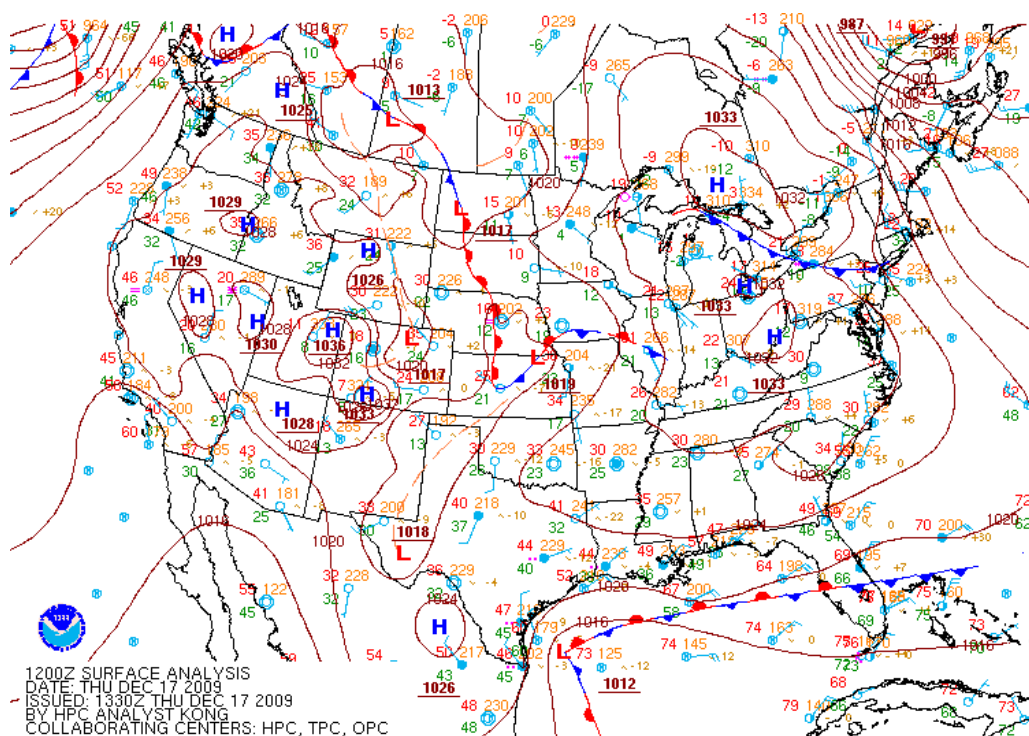


Figure 5. Surface analysis chart, valid 1200 UTC 17 Dec 2009. A newly developed surface low pressure system (1012 hPa) was located over the western Gulf of Mexico with strong high pressure centered over the Ohio Valley region.

emerge along the lee side of the Rocky Mountains. 300 hPa upper-level divergence continued to be in place over southern Texas and would likely begin to increase with the progression of the trough. The 500 hPa jet max over the Mid-Atlantic at 0000 UTC 17 Dec was now offshore and exiting the region. Cyclonic flow can clearly be observed at 500 hPa around the upper-level low over southern Texas. Closer to the surface, 700 hPa and 850 hPa winds were directly from the south and southeast across east Texas, bringing a return of Gulf moisture to the region. This was resulting in a shield of precipitation across the western Gulf of Mexico and the Lone Star state.

Surface observations begin to indicate the development of a surface low pressure system over the western Gulf by 1200 UTC 17 Dec. Atmospheric pressures at the surface near the low were near 1012 hPa with the stationary front still extending to Florida (Fig 5). High

pressure (1033 hPa) was still strongly in place over the eastern U.S.

3.2 0000 UTC to 1800 UTC – 18 Dec 2009

By 0000 UTC on 18 Dec, it was evident that the developing storm system over the western Gulf of Mexico would link up with the deepening trough and move northeast, likely resulting in a winter storm event for eastern North America. Surface analysis showed strengthening of the low pressure system in the western Gulf as it moved northeastward along the stationary front and by 0000 UTC 18 Dec the pressure had fallen to 1006 hPa (Fig. 6a). East of the surface low, southerly winds from the surface to 700 hPa were bringing in vast amounts of moisture over the central Gulf Coast states (Figs. 6b, 6c). Warm air advection (WAA) was also beginning to develop along the stationary front, indicating frontogenesis and a possible transition to a warm front (Fig 6d).

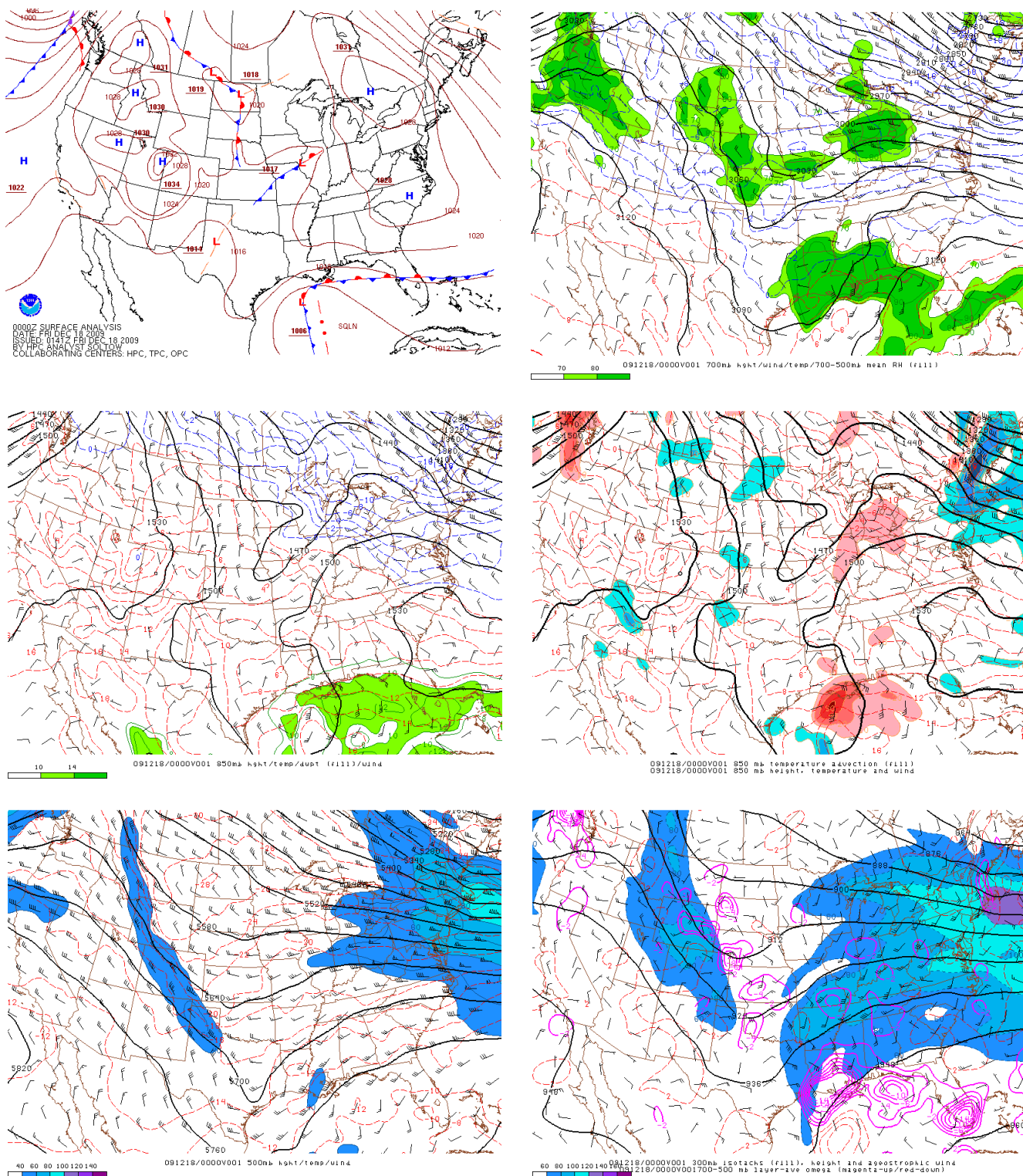


Figure 6. Atmospheric conditions at various heights, each valid 0000 UTC 18 Dec 2009. **A) Top left:** Surface analysis with developing low pressure over western Gulf of Mexico; **B) Top right:** 700 hPa analysis with 700-500 hPa relative humidity (color fill); **C) Middle left:** 850 hPa analysis with dew point (color fill); **D) Middle right:** 850 hPa analysis with warm air advection (red) and cold air advection (blue); **E) Lower left:** 500 hPa analysis with wind velocities (knots, vectors and color fill); **F) Lower right:** 300 hPa analysis with wind velocities and upper level divergence (magenta).

Upper level plots at both 500 and 300 hPa showed a deep trough extending south from the northern Great Plains to the Texas Gulf Coast (Figs. 6e, 6f) at 0000 UTC on 18 Dec. 40 knot winds were associated with a 500 hPa shortwave that was beginning to develop over the north-central Gulf and another shortwave composed of 40-50 knot winds was present over the Rocky Mountains. Along the lee side and southern extent of the trough, upper level divergence (Fig. 6f) was helping to enhance cyclogenesis at the surface. The leading edge of the sub-tropical jet stream (STJ) is apparent over the southern Gulf of Mexico (Figs. 6e, 7a) where winds of 40 to 60 knots were present at upper levels. Strong cyclogenesis can be associated with the presence of both the PJ and STJ along with variations in wind speeds at different heights (Uccellini and Johnson 1979).

By 1200 UTC 18 Dec 2009, precipitation overspread the entire southeast United States with heavier bands located over Mississippi and Alabama. Surface observations and 850 hPa analysis indicated areas receiving precipitation were above freezing as the rain/snow line was located north of the region over the Ohio Valley and into northern Virginia. However, higher elevation areas such as Asheville, North Carolina (KAVL) were beginning to report light snow around 1200 UTC. This was due to snow formation at high altitudes (700-800 hPa) which fell through drier air near the surface, causing evaporative cooling. This cooling brought temperatures down to freezing while continued evaporation eventually resulted in moisture reaching the ground as snow at KAVL. This would continue until WAA overtook the region by 1800 UTC.

Surface pressures were continuing to decline in association with the surface low which was now located approximately 50 miles south of Mobile, Alabama. As predicted by WAA from the 0000 UTC 850 hPa analyses, a warm front now existed over northern Florida and southern Alabama; a cold front stretched south from the center of the surface low to just west of Cuba.

The high pressure system over the eastern U.S. at 1200 UTC on 17 Dec was now primarily located over New England with a pressure of 1030 hPa (a slight 3 hPa decrease in pressure from 1200 UTC 17 Dec). This positioning allowed northeast winds around the high to channel cold air into the region east of the central Appalachians. Below freezing conditions now existed near the surface from southwest Virginia north and east into the Mid-Atlantic and New England regions. The thermodynamic sounding from Roanoke, Virginia (KRNK) at 1200 UTC indicated that temperatures were near 0°C . Eventually, warm air aloft would erode, giving way to the sub-freezing temperatures required for ice crystal formation.

Boundary-layer convergence, coupled with upper-level divergence at 300 hPa, was helping to strengthen the low pressure system over the north-central Gulf. Upward vertical velocities (Ω) were highest over Alabama, which corresponded well with precipitation and strong WAA occurring over that same region. Subsidence was present along the backside of the system with the advent of dry CAA at 850 hPa from the northwest. This strong advection of cold, dry air tightened the moisture gradient around the cyclone, helping to enhance the comma pattern seen on satellite imagery (not shown).

3.3 1800 UTC – 18 Dec 2009 to 1200 UTC – 19 Dec 2009

As the upper level trough progressed eastward, a shortwave at 500 hPa developed over the southern Appalachians by 1800 UTC on 18 Dec 2009. Winds at this level were between 40 and 70 knots, while at 300 hPa, winds were approaching 100 knots (Figs. 8a, 8b). Upper level divergence was also notable over the region within the left-front quadrant of the shortwave. Average upward vertical velocities between 700 and 500 hPa were also relatively high (-8 to $-14\ \mu\text{bar/sec}$) as shown in Figure 8c. This upper level support was helping to enhance precipitation with the heaviest

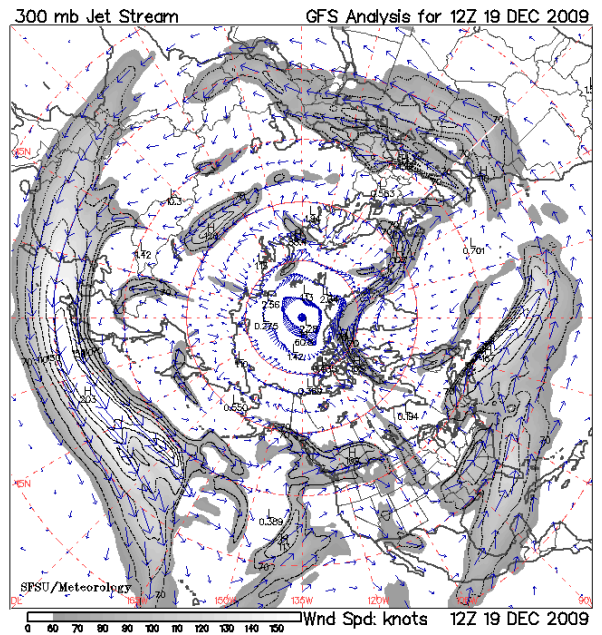
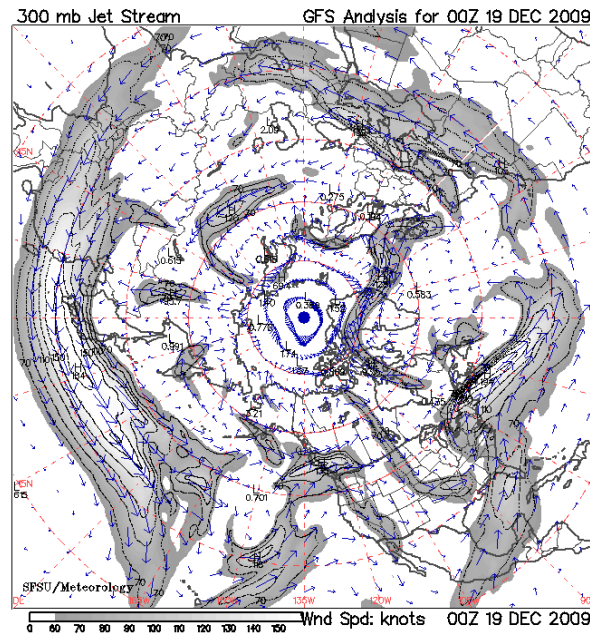
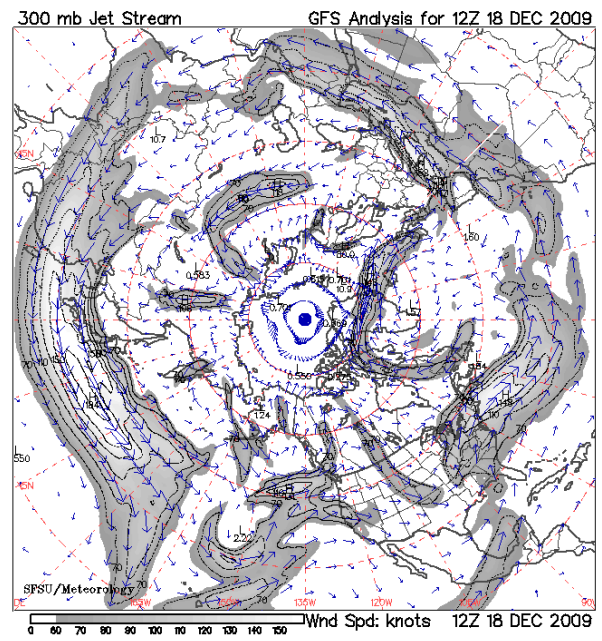
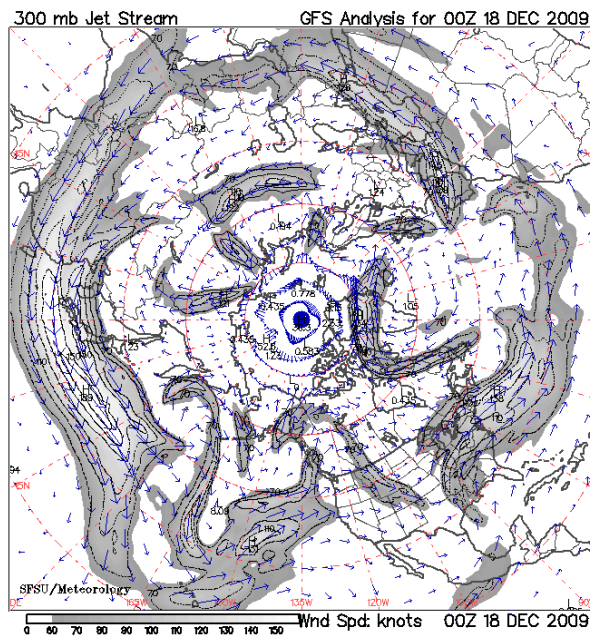


Figure 7. Global Forecast System (GFS) analysis of 300 hPa jet stream pattern over the Northern Hemisphere, valid **A) Top left:** 0000 UTC 18 Dec 2009; **B) Top right:** 1200 UTC 18 Dec 2009; **C) Lower left:** 0000 UTC 19 Dec 2009; **D) Lower right:** 1200 UTC 19 Dec 2009. Note the merger of the polar jet (PJ) with the sub-tropical jet (STJ) over the southeastern United States from 0000 UTC 18 Dec to 1200 UTC 19 Dec 2009.

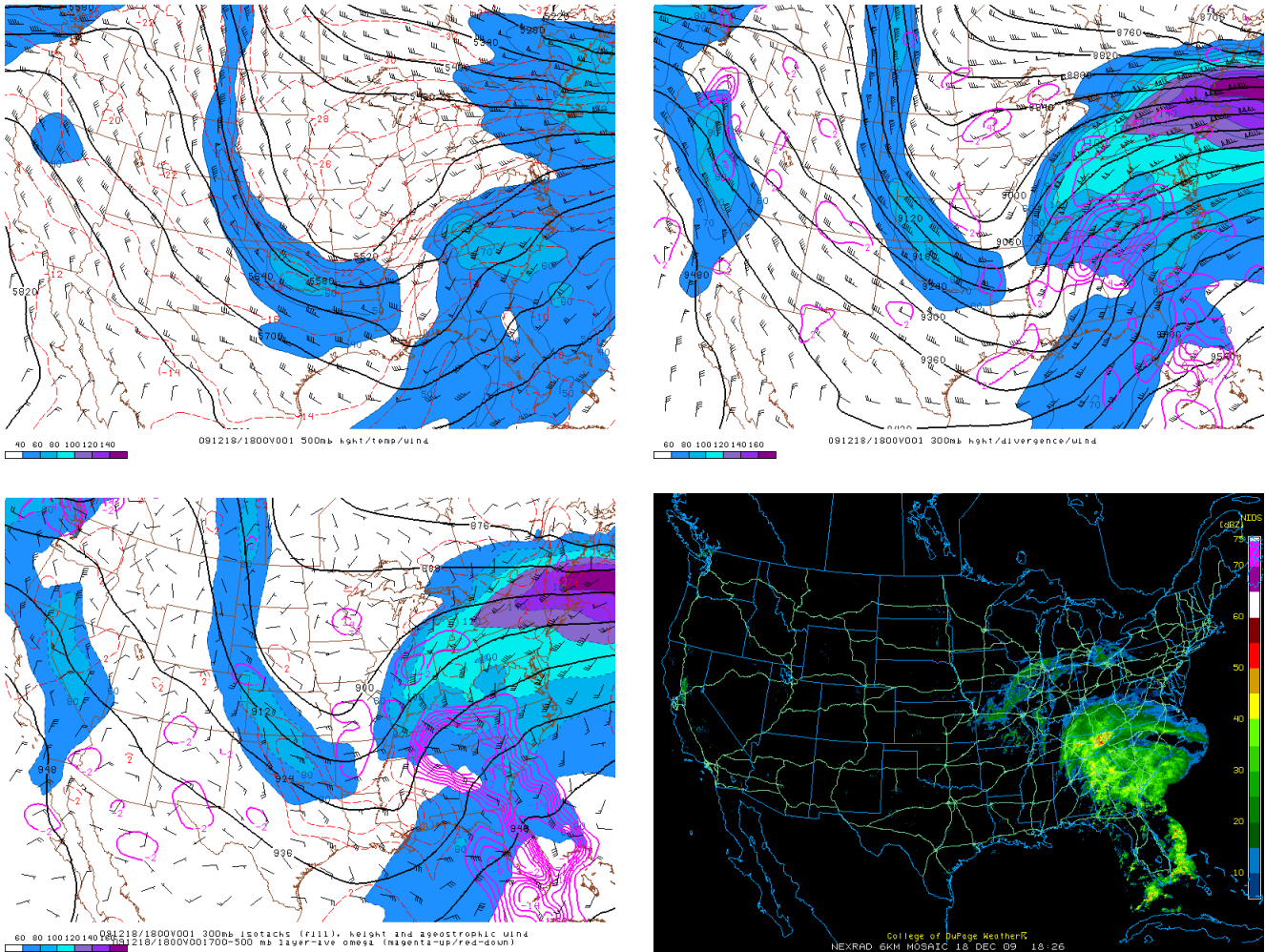


Figure 8. Atmospheric conditions at various heights, each valid 1800 UTC 18 Dec 2009. **A) Top left:** 500 hPa analysis with wind (vectors and color fill) values; **B) Top right:** 300 hPa analysis with wind (vectors and color fill) and divergence (magenta lines); **C) Lower left:** 300 hPa analysis with wind (vectors and color fill) along with 700 to 500 hPa average Omega values (magenta lines); **D) Lower right:** WSR-88D mosaic image valid 1826 UTC 18 Dec 2009.

amounts occurring along the eastern-facing slopes of the Blue Ridge and Appalachians (where upslope flow was occurring). The precipitation was in the form of snow for the high country of Tennessee, Kentucky, western North Carolina, and Virginia while low elevation locales were receiving rain (Fig. 8d). With such strong upward forcing, the Storm Prediction Center (SPC) in Norman, Oklahoma issued their first mesoscale discussion (MD #2257) concerning heavy snow over the southern Appalachians and Blue Ridge

mountains at 1832 UTC. The following is an excerpt from that discussion:

"HEAVY SNOWFALL RATES AROUND 1 INCH PER HOUR WILL LIKELY COMMENCE FIRST ACROSS THE HIGHER ELEVATIONS OF THE SRN APPALACHIANS IN THE 18-21Z PERIOD WITH MIXED PRECIPITATION OCCURRING ACROSS WRN PORTIONS OF THE NC PIEDMONT. THE HEAVY SNOWFALL RATES WILL EXTEND NEWD INTO SWRN VA AND SERN WV 21-00Z. LOCALIZED RATES AROUND 2 INCHES PER HOUR WITH POTENTIALLY HEAVIER BURSTS ARE POSSIBLE OVER

E FACING SLOPES IN WRN NC AND
PERHAPS SW VA LATE THIS
AFTERNOON INTO THE EVENING
HOURS."

The discussion also mentions the detection of lightning over western North Carolina, a sign of strong convection and possible thunder snow.

At 1800 UTC, the surface low pressure (998 hPa) was located over the western Florida panhandle. A second weaker low was situated over central Illinois (1010 hPa) and associated with an upper level disturbance moving northeast. High pressure (1027 hPa) was still in control over the northeast while ridging along the west coast provided for the development of strong high pressure (1034 hPa) over the intermountain west.

Over the next several hours the mid-latitude cyclone moved further northeast and by 0000 UTC on 19 Dec 2009, was located over Savannah, Georgia. Its atmospheric pressure was now 996 hPa. A nearly stationary warm front extended northeast from the center of the low while a cold front was draped south across the western Caribbean as far as Cuba. High pressure to the north into New England finally began to retreat back into central Canada over the Hudson Bay; however, temperatures were well below freezing across most of eastern North America (Fig 9a).

The mid-level 700 hPa analysis at 0000 UTC 19 Dec indicated high moisture content over the southeast U.S. stretching north and west into the Ohio Valley (Fig. 9b). Easterly winds were providing return flow off of the Atlantic Ocean and into the southeast. Excess moisture within cold clouds began to undergo heterogeneous nucleation most likely through contact freezing (or possibly condensation freezing). With atmospheric temperatures

below -8°C at 700 hPa, dendritic snow growth would be expected, which results in wet, heavy snowfall (Stull 2000). The SPC issued MD #2258 at 0022 UTC, again, concerning heavy snowfall rates of one to two inches per hour across Virginia, southern West Virginia and northern North Carolina.

850 hPa analysis at 0000 UTC 19 Dec indicated sub-freezing temperatures across northern Georgia and into western North Carolina/eastern Tennessee along with points north of the Virginia/North Carolina state line (Fig. 9c). Here too, easterly winds off the Atlantic were providing a rich moisture feed to the mountainous locations for heavy snow development. A sharp rain/snow gradient formed over northern Georgia and western South Carolina where WAA was occurring near the surface front (Fig. 9d). Areas to the north of the WAA saw primarily snow while those areas undergoing advection saw a mixture of rain, sleet, and freezing rain.

The shortwave located at 500 hPa was now located primarily over Virginia and North Carolina (Fig. 9e) by 0000 UTC 19 Dec. This, coupled with upper level divergence at 300 hPa (Fig. 9f), 500 to 700 hPa average Omega values of $-14 \mu\text{bar/sec}$ (Fig. 10a), and the merging of the PJ and STJ (Fig. 7c, 7d) were helping to enhance heavy snow throughout the Atlantic region (Fig. 10b). Infrared satellite imagery taken at 0000 UTC 19 Dec, 2009 indicates a strong influx of Gulf and Atlantic moisture into the storm system by way of the subtropical jet (Fig. 11).

3.4 1200 UTC – 19 Dec 2009 to 0000 UTC – 20 Dec 2009

Snow continued to overspread the Mid-Atlantic, reaching northern Pennsylvania and New York City by 1200 UTC on 19 Dec.

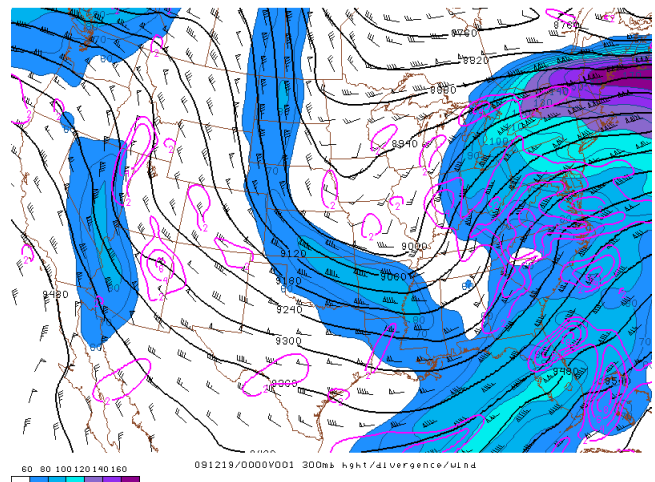
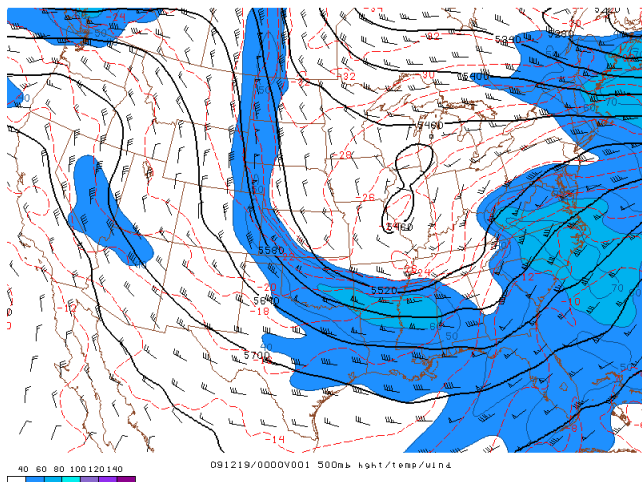
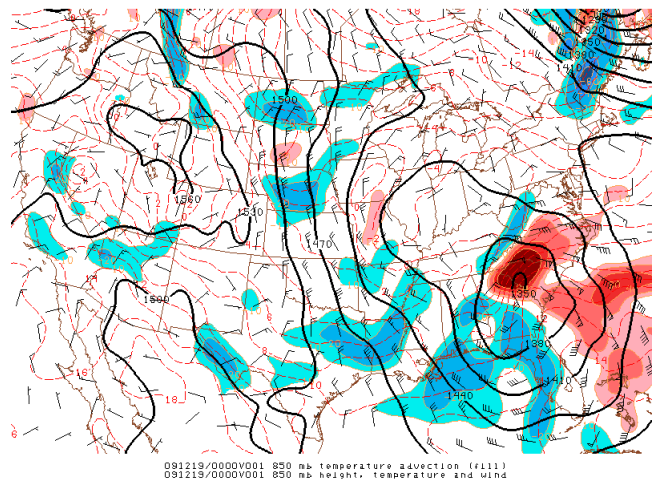
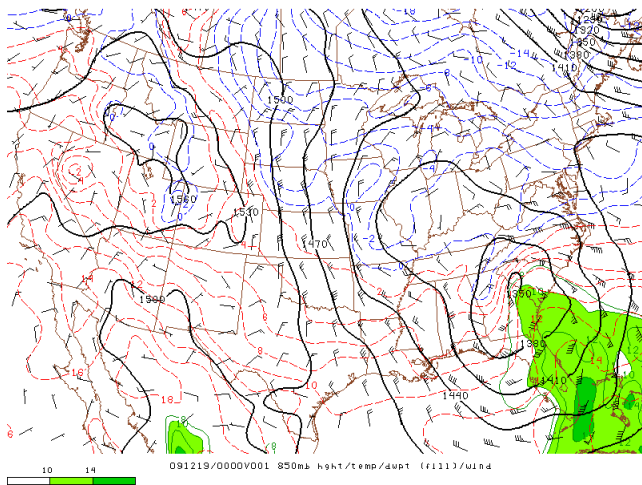
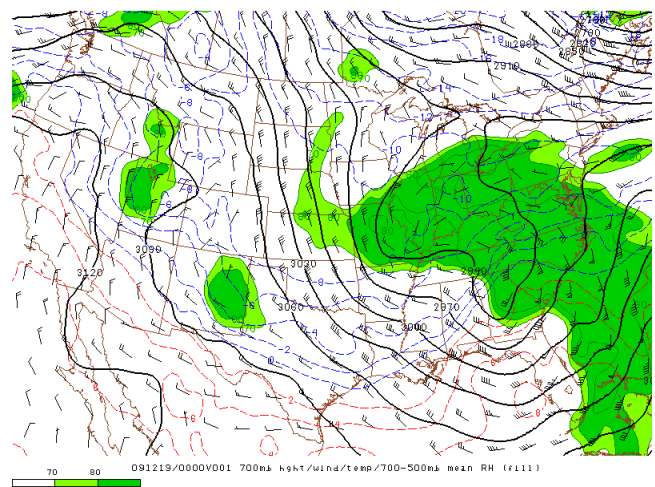
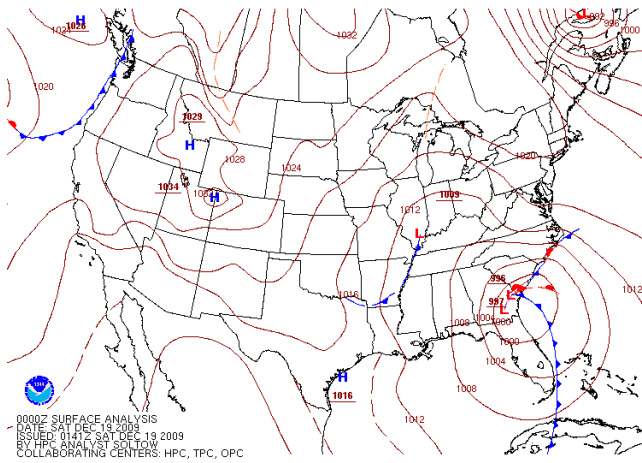


Figure 9. Atmospheric conditions at various heights, each valid 0000 UTC 19 Dec 2009. **A) Top left:** Surface analysis with low pressure located over Savannah, Georgia; **B) Top right:** 700 hPa analysis with 700-500 hPa relative humidity (color fill); **C) Middle left:** 850 hPa analysis with dew point (color fill); **D) Middle right:** 850 hPa analysis with warm air advection (red) and cold air advection (blue); **E) Lower left:** 500 hPa analysis with wind velocities (knots, vectors and color fill); **F) Lower right:** 300 hPa analysis with wind velocities and upper level divergence (magenta).

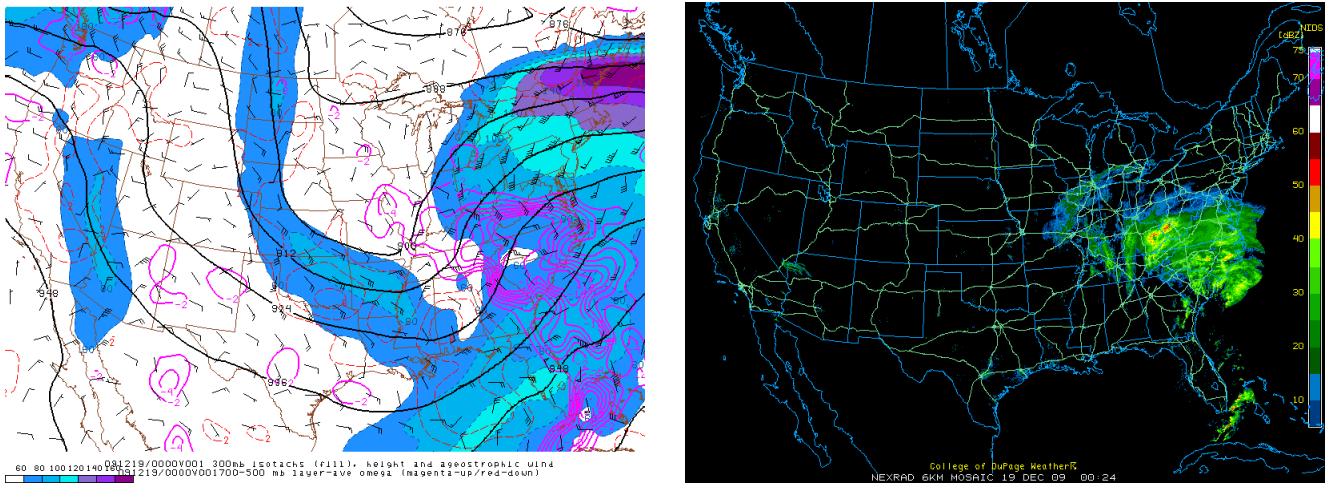


Figure 10. A) Left: 300 hPa analysis with wind (vectors and color fill) and divergence (magenta lines) valid 0000 UTC 19 Dec 2009; **B) Right:** WSR-88D mosaic image valid 0024 UTC 19 Dec 2009

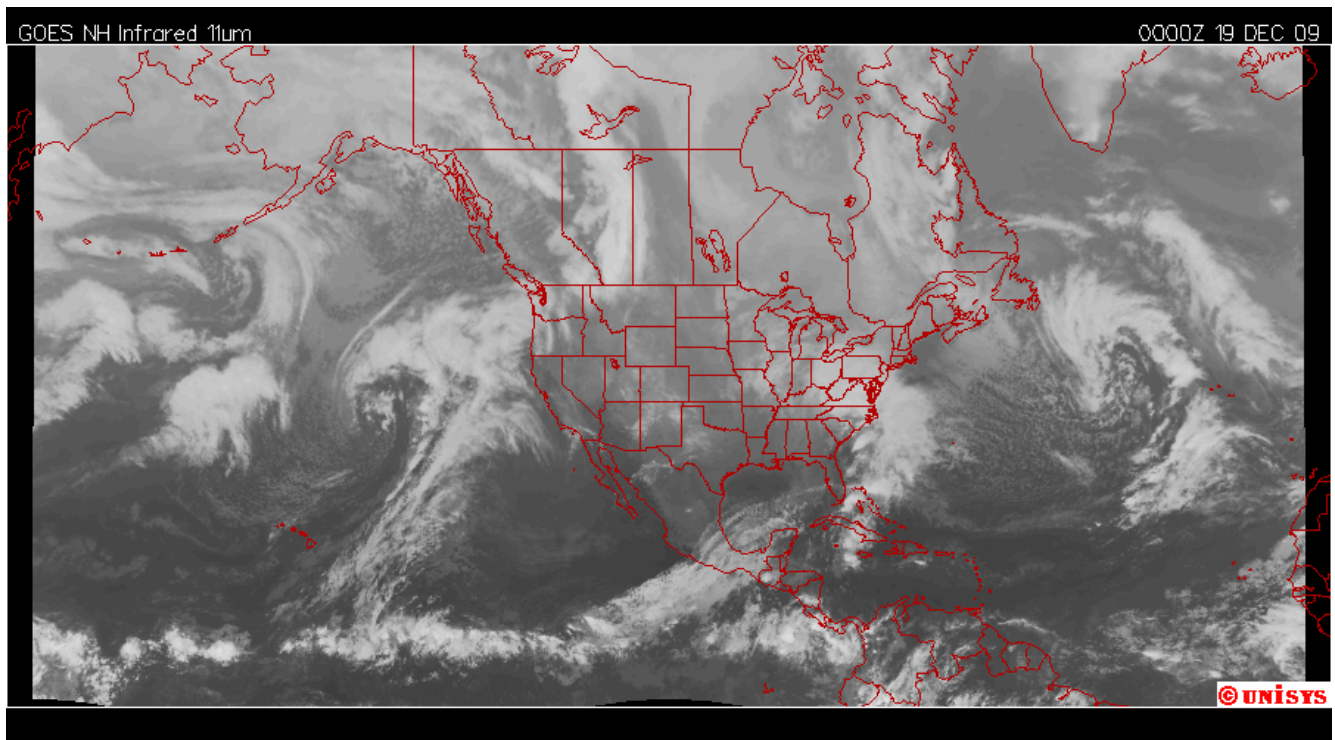


Figure 11. Infrared satellite image from GOES, valid 0000 UTC 19 Dec 2009. Note the position of the subtropical jet stream (STJ) over the central Pacific Ocean and its shift northeast to interact with the polar jet stream (PJ) over the eastern United States. Also note the comma shape to the cyclone over the Mid-Atlantic region.

Surface analysis placed a well-defined 986 hPa mid-latitude cyclone over the Outer Banks of North Carolina (Fig. 12a). Although the system showed signs of an occlusion, this was not an indication of weakening. Mid and upper level support (discussed below) were still in place at 1200 UTC for continued strengthening of the system as it made its way off to the northeast. With the deepening of the surface low and a strong area of high pressure (1022 hPa) situated over southeast Canada, a fairly compact pressure gradient was present over the Mid-Atlantic. The National Weather Service out of Biltmore MD/Washington D.C. began issuing Blizzard Warnings at approximately 0406 UTC on 19 Dec 2009. By 1500 UTC, these warnings included the Washington D.C., Baltimore, MD, and Annapolis, MD metro areas as well as the following counties in Virginia: Arlington, Fairfax, King George, Prince William, Spotsylvania, and Stafford; and in Maryland: Baltimore, Harford, Howard, and Montgomery. Further to the north, Blizzard Warnings were already in effect for Long Island, New York and southern New London County, Connecticut (since 1800 UTC 18 Dec).

By 1200 UTC on 19 Dec, the SPC had issued MD #2260 which discussed heavy snowfall over northern Virginia, Maryland, Delaware, and southern New Jersey. Two to three inches of snow per hour were expected to fall over this region with one to two inches per hour in surrounding areas (Pennsylvania and West Virginia).

Low level flow from the east and southeast helped to usher in vast amounts of moisture from the Atlantic. With a supersaturated atmosphere and cold temperatures (-10 to -20°C) present aloft (Figs. 12b, 12c), large dendritic snowflakes could develop. Additional support came from high Omega values (-14 to -16 $\mu\text{bar/sec}$) between 500 and 700 hPa (not shown), strong vorticity advection between 700 and 400 hPa (also not shown), and a strong shortwave (80+ knots) present at 500 hPa over the region (Fig. 12e). The left-front

quadrant of this shortwave was situated over northern Virginia and the Baltimore, MD area; this divergence at 500 hPa coupled with strong divergence at 300 hPa (Fig. 12f) helped to enhance large-scale lift. Strong WAA also played a role in this heavy snow event (Fig. 12d) which, together with deep frontogenesis, resulted in persistent heavy snow banding. Table 1 includes total snowfall amounts between 1600 UTC 18 Dec to 2000 UTC 19 Dec 2009.

3.5 0000 UTC – 20 Dec 2009 to 0000 UTC – 21 Dec 2009

SPC MD #2262 was issued at 0530 UTC on 20 Dec 2009; the main concern: heavy snowfall rates of one to two inches per hour coupled with 30+ knot surface winds would lead to blizzard conditions over Long Island and southern Connecticut. An analysis of surface conditions indicated that the low pressure system had remained nearly stationary off the Mid-Atlantic coast for nearly twelve hours. By 0000 UTC 20 Dec, it was situated approximately 200 miles southeast of New Jersey with a minimum central pressure of 981 hPa (Fig. 13a). An occlusion stretched eastward for another 200 miles before it transitioned into a warm front south of the main area of WAA and a cold front extended from the triple point southeast toward Bermuda. High pressure near the Hudson Bay in Canada was ushering in cold north winds across New England and into the Midwest U.S. Moisture was still present over the region within the ice crystal formation layer (Fig. 13b). Upper level dynamics still supported continued strengthening of this system. 850 hPa WAA/CAA (Figs. 13c, 13d) along with a strong jet streak (Fig. 13e) and 300 hPa divergence (Fig. 13f) helped to deepen the surface low.

By 0900 UTC 20 Dec, the system “bombed out” with a central low pressure of 976 hPa. After this point in time, the cyclone began to lose strength due to a number of factors. Water

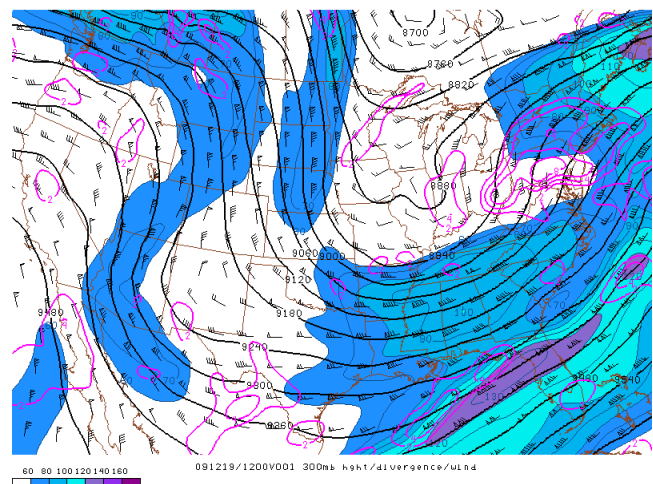
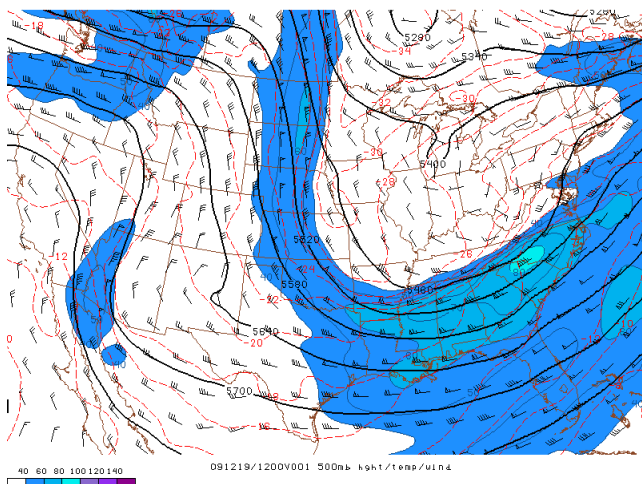
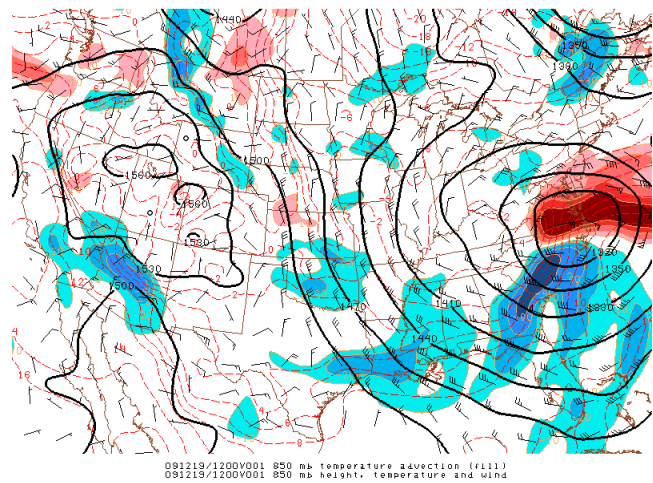
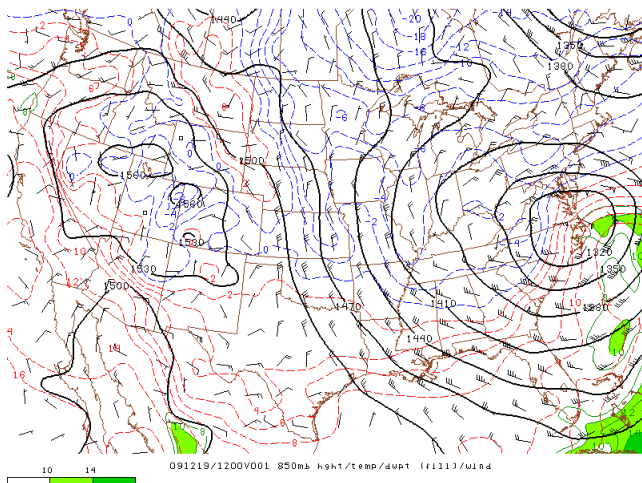
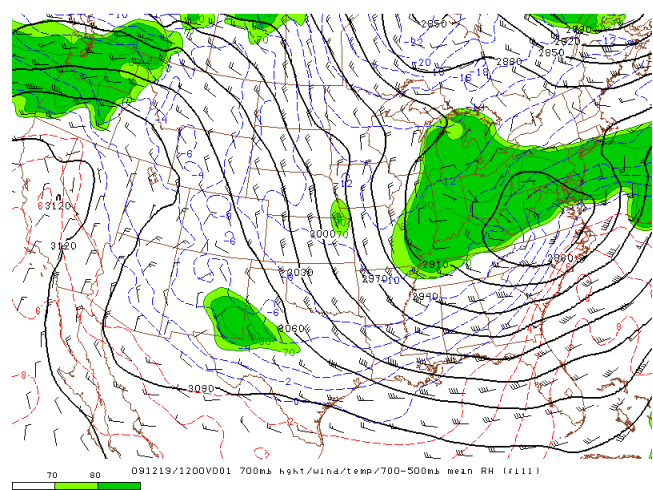
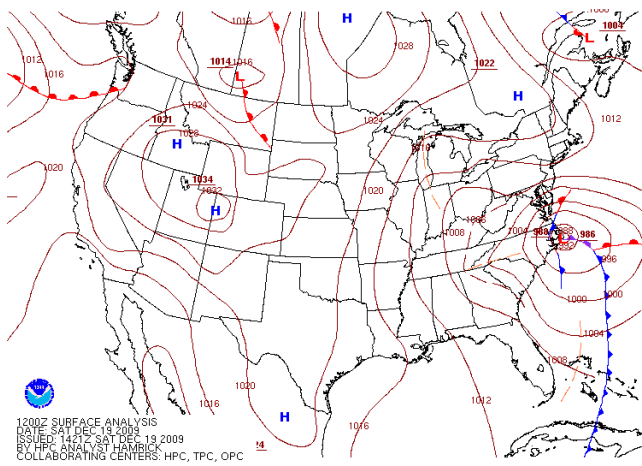


Figure 12. Atmospheric conditions at various heights, each valid 1200 UTC 19 Dec 2009. **A) Top left:** Surface analysis; **B) Top right:** 700 hPa analysis with 700-500 hPa relative humidity (color fill); **C) Middle left:** 850 hPa analysis with dew point (color fill); **D) Middle right:** 850 hPa analysis with warm air advection (red) and cold air advection (blue); **E) Lower left:** 500 hPa analysis with wind velocities (knots, vectors and color fill); **F) Lower right:** 300 hPa analysis with wind velocities and upper level divergence (magenta).

Location	State	Snow (inches)
WOODSIDE	DE	11
WILMINGTON	DE	8.7
SMYRNA	DE	8
DOVER	DE	5
RAWLINGS	MD	16
GERMANTOWN	MD	15.5
WALKERSVILLE	MD	15.5
BRYANS ROAD	MD	14.5
SILVER SPRING	MD	14.2
COLUMBIA	MD	14.1
GARRISON	MD	12.4
BOWIE	MD	11
ANNAPOLIS	MD	10.5
BALTIMORE	MD	7.5
SHILOH	NJ	10.5
MILLVILLE	NJ	9.5
LONG BEACH ISLAND	NJ	8.5
BRIDGETON	NJ	8
CHERRY HILL	NJ	8
HAMMONTON	NJ	7.5
SEWELL	NJ	6
ESTELL MANOR	NJ	5.5
ATLANTIC CITY	NJ	5.4
OCEAN CITY	NJ	5
BRIDGEPORT	OH	5
HANOVER	PA	16
HOLTWOOD	PA	16
ORRTANNA	PA	14
UPPER STRASBURG	PA	14
BONNEAUVILLE	PA	13
GETTYSBURG	PA	10
SHIPPENSBURG	PA	10
PHILADELPHIA	PA	8.8
BEDFORD	PA	8
PITTSBURGH WFO	PA	4
INDIAN VALLEY	VA	26
CROZET	VA	23
COVINGTON	VA	22.6
BALLSTON	VA	16.5
DULLES INTERNATIONAL	VA	16

Table 1 cont.,

Location	State	Snow (inches)
CHARLOTTESVILLE	VA	15
BLACKSBURG	VA	14.2
REAGAN NATIONAL ARPT	VA	13
ALEXANDRIA	VA	12
RICHMOND W	VA	11.5
MARLINTON	WV	26
FRIARS HILL	WV	25
JUMPING BRANCH	WV	24
WILLIAMSBURG	WV	22
GRANDVIEW	WV	21
BECKLEY	WV	20
CHARLES TOWN	WV	18
ELKINS	WV	18
HINTON	WV	17
PRINCETON	WV	17

Table 1. Snow accumulation totals recorded from 1600 UTC 18 Dec to 2000 UTC 19 Dec 2009 for various locations arranged by state and state snowfall total.

Vapor imagery from 0832 UTC indicated dry air being wrapped around the low pressure system, effectively cutting off the flow of warm, moist air to the system (Fig. 14). The stacking of heights from the surface to 500 hPa was also weakening the system. Without the upper level support, the cyclone figuratively “smothered itself.” The cyclone was no longer aligned with the shortwave moving through the long wave Rossby pattern, further limiting upper level support. With regards to upward vertical velocities over the region, they too showed signs of weakening by 0900 UTC 20 Dec.

By 1200 UTC the cyclone was off the coast of Maine and by 2100 UTC the low pressure system was situated off the coast of Nova Scotia, Canada, completely occluded.

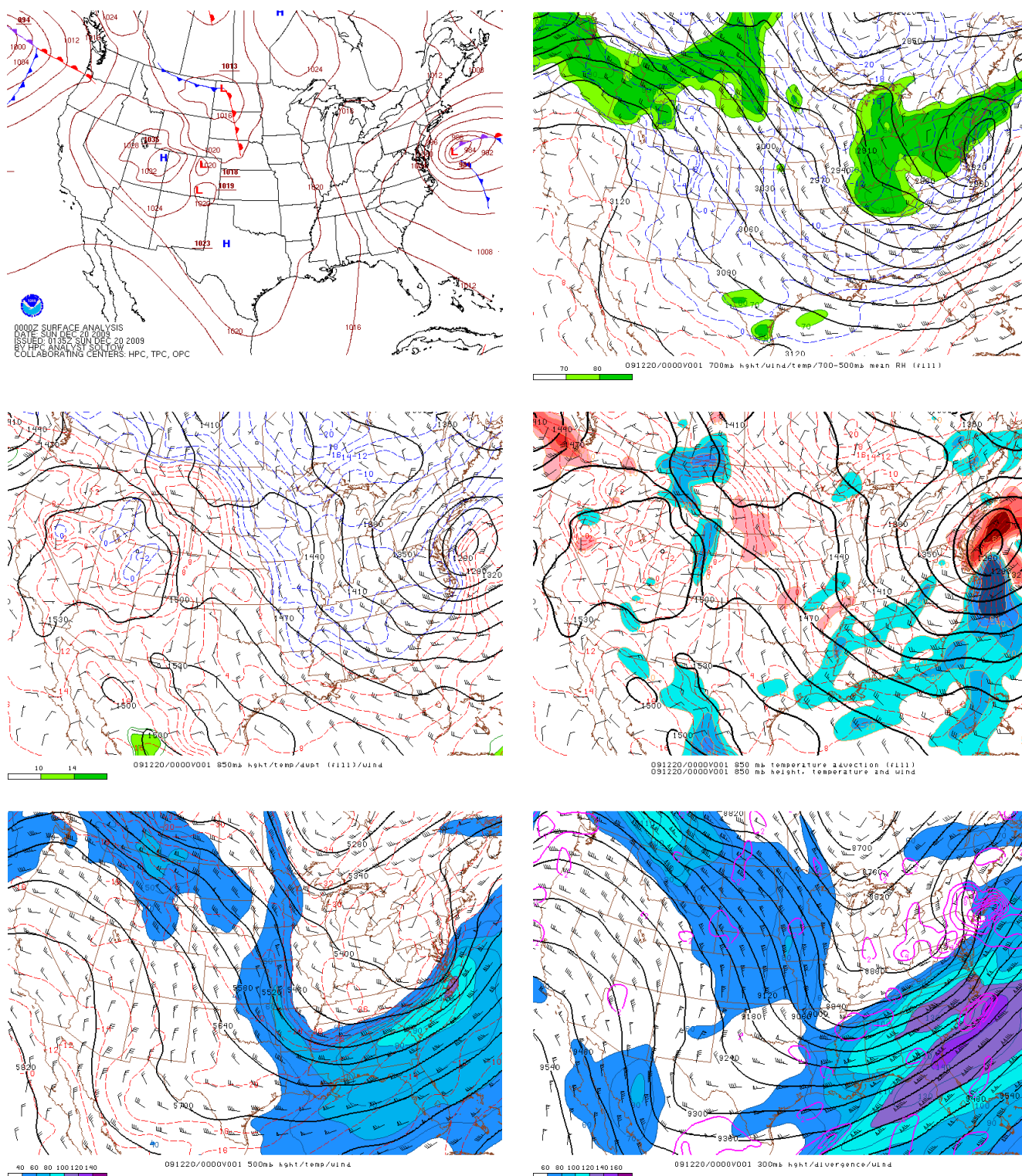


Figure 13. Atmospheric conditions at various heights, each valid 0000 UTC 20 Dec 2009. **A) Top left:** Surface analysis; **B) Top right:** 700 hPa analysis with 700-500 hPa relative humidity (color fill); **C) Middle left:** 850 hPa analysis with dew point (color fill); **D) Middle right:** 850 hPa analysis with warm air advection (red) and cold air advection (blue); **E) Lower left:** 500 hPa analysis with wind velocities (knots, vectors and color fill); **F) Lower right:** 300 hPa analysis with wind velocities and upper level divergence (magenta).

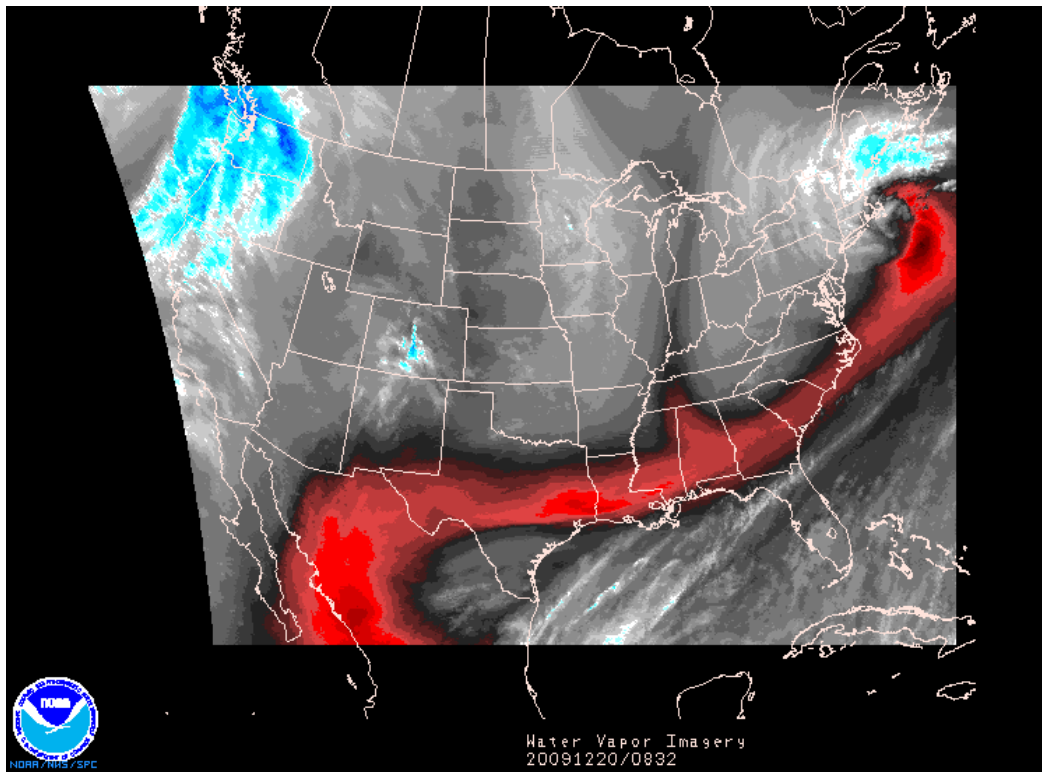


Figure 14. Water vapor imagery, valid 0832 UTC 20 Dec 2009. Significant dry air advection into the storm over New England began weakening the system after 0900 UTC.

Although it remained a potent system with an atmospheric pressure of 968 hPa and tightly packed pressure gradients, the cyclone was making its way out into the cold, open waters of the North Atlantic.

4. STORM IMPACTS

Blizzard conditions were experienced in several locations over the eastern United States, including Washington, D.C. where whiteout conditions were observed at Reagan National, Dulles International, and Thurgood Marshall International Airports. Further to the north, more than 800 flights at New York's three major airports were canceled (Berger 2009). Figure 15 shows the counties and major cities under winter weather advisories issued from 0000 UTC 17 Dec to 0000 UTC 21 Dec 2009. Graduated circles for each city indicate the year 2000 population (larger circle equals larger

population). From this map, many of the largest cities on the east coast were clearly affected by this storm system.

Road travel was also limited. In West Virginia along Interstate 77 near Beckley, motorists were stranded for up to 18 hours due to heavy snow on the roads. Interstate 81 near Roanoke and Christiansburg, Virginia was also hazardous with dozens of accidents reported to the Virginia State Police.

Seven deaths in Virginia, North Carolina, Ohio, West Virginia, and Pennsylvania were reportedly due to the storm. One death in Pennsylvania occurred when a snowmobile crashed head-on into an Amish buggy (McFadden and Berger 2009).

The blizzard was rated a "Category 2" on the Northeast Snowfall Impact Scale (NESIS). Figure 16 shows the overall total snowfall

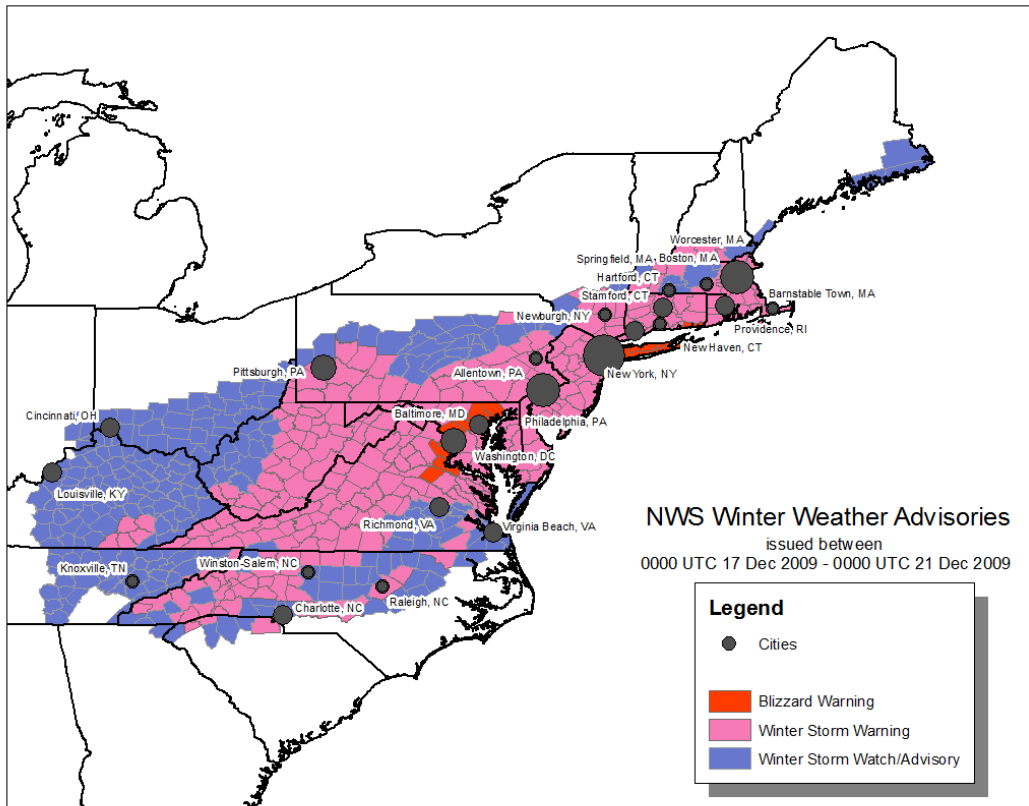


Figure 15. National Weather Service winter weather advisories issued between 0000 UTC 17 Dec to 0000 UTC 21 Dec 2009. City population is graduated with larger circles indicating larger populations. Standard NWS color codes were used for each advisory criterion.

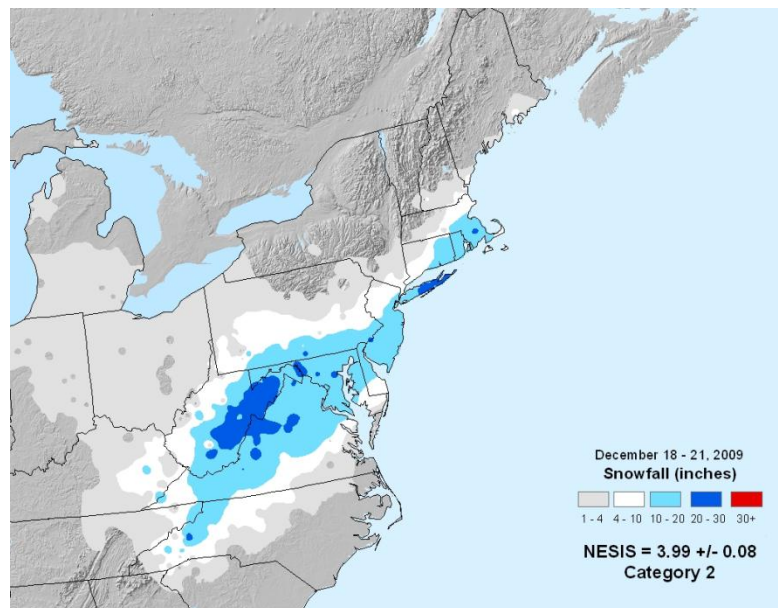


Figure 16. Total snowfall amounts for the event. NESIS score and category are also listed. Image courtesy of NCDC.

amounts across the eastern U.S. Table 2 provides specific snowfall totals for various locations from North Carolina to Maine.

Location	State	Snow (inches)
BOURNE	MA	21.5
KINGSTON	MA	21
NEW BEDFORD	MA	20
MIDDLEBORO	MA	18.5
MENDON	MA	17
HAMPSTEAD	ME	5.4
HAMPTON	ME	5
KITTERY POINT	ME	4.5
WEST GREENWICH	RI	22
WARREN	RI	21
NEWPORT	RI	20.5
SOUTH KINSTOWN	RI	19.9
PORTSMOUTH	RI	19.5
CLINTON	CT	20
EAST HADDAM	CT	20
NORWICH	CT	20
PUTNAM	CT	20
GROTON	CT	18
EAST KILLINGLY	CT	15.7
AMERICAN UNIVERSITY	DC	16
THE MALL	DC	16
DOVER	DE	18
BEAR	DE	17
WILMINGTON	DE	17
NEWARK	DE	16.1
HARLAN	KY	7
BEATTYVILLE	KY	6
WILLIAMSBURG	KY	6
OLNEY	MD	23.3
BETHESDA	MD	23
COLUMBIA	MD	23
DERWOOD	MD	23
SIMPSONVILLE	MD	22.9
GAITHERSBURG	MD	22
ROBBINSVILLE	NC	24

Location	State	Snow (inches)
ASHEVILLE	NC	17
BOONE	NC	16
EAST MARION	NC	15
RUTHERWOOD	NC	15
GREENSBORO	NC	4.5
FOLSOM	NJ	25.7
SWEDESBORO	NJ	25
TABERNACLE	NJ	24.8
ATCO	NJ	24
UPTON	NY	26.3
MOUNT SINAI	NY	24
ISLIP	NY	23.9
SAG HARBOR	NY	20
BRIDGEPORT	OH	5
PHILADELPHIA INTL ARPT	PA	23.2
SHARON HILL	PA	23
SOUTH MOUNTAIN	PA	22
BROGUE	PA	20
INDIAN VALLEY	VA	26
MUSTOE	VA	25.4
FISHERVILLE	VA	25
ROCKY BAR	VA	24
CROZET	VA	23
COVINGTON	VA	22.6
CENTREVILLE	VA	22
DULLES INTERNATIONAL	VA	16
REAGAN NATIONAL ARPT	VA	15.4
MARLINTON	WV	26
FRIARS HILL	WV	25
HORSE SHOE RUN	WV	25
BECKLEY	WV	24
HENDRICKS	WV	24
JUMPING BRANCH	WV	24

Table 2. Snow accumulation totals recorded from 1600 UTC 18 Dec to 2000 UTC 19 Dec 2009 for various locations arranged by state and snowfall total.

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